A Unified Approach to Passive and Active Ocean Acoustic Waveguide Remote Sensing

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OBJECTIVES AND APPROACH

Ocean acoustic waveguide remote sensing (OAWRS) is the basis for the primary undersea surveillance systems of the US Navy for both passive and active detection, localization, imaging and monitoring. Here OAWRS refers to all applications of acoustic remote sensing in an ocean waveguide. The primary objective of this work is to continue the data analysis and model development initiated in a series of major ocean acoustics experiments the PI has conducted, which has been summarized in an invited paper in IEEE Spectrum [1].

We applied fundamental physical and statistical principles inherent in waveguide propagation and scattering to advance the state of the art in undersea surveillance. The approach was to use the extensive data analysis, software and fundamental waveguide scattering, propagation, reverberation and statistical models developed by the PI, his collaborators, graduate students and sub-contractors during the various experimental programs the PI has directed.

WORK COMPLETED/RESULTS

Bistatic, long-range measurements of acoustic scattered returns from vertically extended, air-filled cylindrical targets were made during three distinct field experiments [2-6] in fluctuating continental shelf environments. It is shown that Sonar Equation estimates of mean target-scattered intensity lead to large errors, differing by an order of magnitude from both the measurements and waveguide scattering theory. This is because the sonar equation approximation is not generally valid for targets with directional scatter functions in an ocean waveguide. The use of the Ingenito scattering model is also shown to lead to significant errors in estimating mean target-scattered intensity in the field experiments because they were conducted in range-dependent ocean environments with large variations in sound speed structure over the depth of the targets, scenarios that violate basic assumptions of the Ingenito model. A Greens' theorem based full-field model (VETWS) [7] that describes scattering from vertically extended cylindrical targets in range-dependent ocean waveguides by taking into account non-uniform sound speed structure over the target's depth extent is shown to accurately describe the statistics of the targets' scattered field in all three field experiments [8]. To account for the scintillation in the measured scattered intensity caused by fluctuations of the ocean waveguide [9,10], Monte-Carlo simulations of the scattered field are computed by implementing the full-field model in a range-dependent environment randomized by internal waves [9]. Returns from the man-made target are also

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shown to have a very different spectral dependence from the dominant fish clutter measured in each experiment, suggesting that multi-frequency measurements may be used to help distinguishing fish from man-made targets.

Many species of animals including fish, birds, insects and other self-propelled particles (SPPs) are known to form groups that move in an organized fashion. A fluid dynamic theory is being developed to describe collective behavior of animal groups [11]. Starting from the simple behavioral rule that each individual picks the average velocity of all neighbors within its region of perception, we are beginning to show that SPP groups behave as a fluid over spatial scales much larger than the mean spacing between individuals. We are also beginning to show the existence of a critical population density where each particle needs at least one neighbor within its region of perception on average to sustain synchronous motion within the SPP group, and that disturbances can propagate as waves within a group at speeds much higher than that of any individual [3,4]. These findings may explain how rapid information transfer can occur within animal groups, which may ultimately help maintain long-range order.

A feasibility study for using the low frequency wide area OAWRS method [1,3-6] to (1) instantaneously detect, image and spatially chart ground fish populations, with emphasis on cod and haddock, and (2) continuously monitor the areal densities and behavior of these fish populations over time during their spring spawning season in Ipswich, Massachusetts, and Cape Cod Bays in the Gulf of Maine is proposed. Simultaneous conventional line-transect methods can be used for local calibration of OAWRS areal fish population densities and ground truth species identification. Experimental sites are being considered based on decades of annual Massachusetts State and National Marine Fishery Services surveys of the spawning grounds of Atlantic cod and haddock along the Massachusetts and New Hampshire coastline. The March to June time period is considered to be optimal since it coincides with spawning migration of cod, which are known to congregate in denser groups near the Massachusetts coast. The modeled acoustic target strength, corresponding to an individual cod and haddock with measured fish length distribution and in-situ depth distribution shows strong resonant response in the low frequency range. The modeled target strength varies with actual fish depth as well as neutral buoyancy depth, which is determined by the amount of air in its swimbladder [5,6] and accurately follows the measured resonance frequency of both cod and haddock. A stochastic propagation model [3-6] that has been successfully used in all past OAWRS experimental designs is applied to determine the OAWRS detection levels, as a function of range, for various fish layer thickness and densities at various depths by comparing the modeled scattered returns from fish aggregations to the modeled reverberation from seafloor. Preliminary results show that typical aggregations of cod and haddock like those measured by conventional fishery echo-sounder will stand above returns from the seafloor by at least two orders of magnitude, even if they are only within 1 m of the seafloor, when probed at their predicted resonance frequency.

Ocean acoustics in the changing Arctic environment will be investigated in a focused three-week field experiment conducted jointly with Institute of Marine Research (IMR) Norway in the Nordic Seas. This will include the first use of new NSF OAWRS source and receiver arrays to enable instantaneous continental-shelf scale imaging and continuous monitoring of fish and whale populations. Acoustic resonant scattering responses of spawning Nordic Sea capelin, cod, and Norwegian herring have been predicted based on a widely used model for resonant scattering from a fish swimbladder using available in-situ measurements or typical values of fish population densities, depth distribution, fish body lengths, and neutral buoyancy depths. Preliminary results show that the swimbladder resonance frequency varies significantly across the three species, as does the overall spectral response, which

makes remote species classification possible. Preliminary modeled dynamic range in population density expected in OAWRS imaging for capelin, cod and herring shows that each species is highly conducive to OAWRS imaging, with modeled scattered returns from fish aggregations standing above the modeled reverberation from seafloor by at least two orders of magnitude at typical shoaling densities.

Preliminary analysis shows that humpback whale behavior is synchronous with peak annual Atlantic herring spawning processes in the Gulf of Maine [12]. With a passive, wide-aperture (189-m), densely-sampled (160-element), coherent hydrophone array towed north of Georges Bank in a Fall 2006 OAWRS experiment [4-6], vocalizing whales can be instantaneously detected and localized over most of the Gulf of Maine ecosystem in a roughly 400-km diameter area by introducing array gain orders of magnitude higher than previously available in acoustic whale sensing. With humpback whale vocalizations consistently recorded at roughly 2000 per day, we can determine their spatial locations over time by introducing a synthetic aperture tracking technique [13,14] and the array invariant method [15] to the whale sensing problem. Preliminary results show that vocalizing humpbacks (1) are overwhelmingly distributed along the northern flank of Georges Bank, coinciding with the peak spawning time and location of Atlantic herring, (2) their overall vocalization behavior is strongly diurnal, synchronous with the formation of large nocturnal herring shoals, with a call rate roughly ten-times higher at night than during the day. Preliminary results also show that humpback whale vocalizations are comprised of (1) highly diurnal non-song calls, suited to hunting and feeding behavior, and (2) songs, which have constant occurrence rate over a diurnal cycle, invariant to diurnal herring shoaling.

We have investigated potential ability of a biomimetic acoustic sensing system with a sparse sensor array to detect and localize acoustic clutter in a range-dependent ocean waveguide. An analytic model is being developed by employing low frequency scattering characteristics of acoustic clutter and biological sounds from marine animals revealed during the Fall 2006 OAWRS experiment [4,6]. We have comprehensively identified parameters that could affect the performance of the system such as operating frequency, bathymetry, sound speed structure, and ambient noise level. The detection range of the system has been extensively examined for detection of acoustic clutter, such as geological features or fish aggregations, in continental shelf environments by incorporating the changes in these identified parameters. Preliminary results show that the system can detect targets located at ranges more than 5 km. We have also shown that acoustic detection by the system is noise limited. The effect of various underwater noise sources, both natural and anthropogenic, on acoustic detection will be evaluated quantitatively.

An analytic model that accounts for the coupled effects of accumulated attenuation, dispersion, and Doppler-shift in the acoustic field forward propagated through a fluctuating ocean waveguide is being developed. The novel aspect of this analytic model is to quantify the Doppler-shift effects induced by the time-varying surface gravity and internal waves.

A theory for nonlinear scattering of sound in the presence of inhomogeneities has been derived [16] to potentially enhance the detection of submerged targets. From the equations of mass conservation, momentum conservation and equation of state, the second-order nonlinear wave equation in the presence of inhomogeneities was derived, and a general solution was obtained in the form of a volume integral, which will be evaluated for a number of canonical cases. Preliminary analysis has shown that the nonlinear interaction at the sum and difference frequencies of the primary scattered waves

dominate in the far field, due to the logarithmic range dependence. Approximation of the dominant nonlinear field is obtained by analytic methods.

IMPACT/APPLICATIONS

- We experimentally show that use of the Sonar Equation can lead to significant errors in estimating acoustic scattered returns in a continental-shelf ocean waveguide.
- We are developing an analytic fluid-dynamic theory for collective behavior of animal groups, starting from simple behavioral rules of individuals. This theory can explain some key features observed from large-scale fish schools including the critical population density and the group speed propagation of information within the school.
- The OAWRS method will be applied to explore the abundance, temporal and spatial distribution and behavior of cod and haddock populations in the Gulf of Maine, during their spring spawning seasons in Ipswich, Massachusetts and Cape Cod Bays.
- An OAWRS experiment has been designed to determine the group behavioral mechanisms of vast social groups of three keystone species, capelin, herring and cod, in the Nordic Sea Arctic Ecosystem that govern basic processes such as spawning, migration and response to variations in the ocean environment and whale predators.
- Preliminary results show that humpback whale behavior is synchronous with peak annual Atlantic herring spawning processes in the Gulf of Maine during the Fall 2006 OAWRS experiment.
- We are developing an analytic model to assess long-range detection of acoustic clutter by an acoustic sensing system with sparse sensors in the continental shelf environment.
- We are developing an analytic model that accounts for coupled effects of accumulated attenuation, dispersion, and Doppler-shift in acoustic field forward propagated through a fluctuating ocean waveguide.
- We have developed a theory for nonlinear scattering of sound in the presence of inhomogeneities insonified by two plane waves at slightly different frequencies. Preliminary results show that the nonlinear interaction at sum and different frequencies of primary scattered waves dominate in the far field.

TRANSITIONS

Transition of the Acoustic Clutter Program is already significant as documented by the great amount of Naval Research now focusing on clutter issues in active sonar, which was spearheaded and guided by the PI's various Acoustic Clutter programs. Recently, for example, this work helped start the Office of Naval Research (ONR) - Basic Research Challenge (BRC) program and several other Navy programs that focus on waveguide target scattering, clutter and attenuation.

RELATED PROJECTS

Other organizations participating in the Geoclutter Program are Northeastern University, National Marine Fisheries Service, Institute of Marine Research Norway, NRL, ARL-PSU, MAI, UNH, RESON, SNWSC, and NFESC.

RECENT RELEVANT PUBLICATIONS

1. N. C. Makris, "New Sonar Technology Reveals City-size Schools of Fish: Low-frequency sound waves improve ocean sensing," IEEE Spectrum (August, 2011).
2. P. Ratilal, Y. Lai, D. T. Symonds, L. A. Ruhlmann, J. Goff, C. W. Holland, J. R. Preston, E. K. Scheer, M. T. Garr, and N. C. Makris, (2005) "Long range acoustic imaging of the Continental Shelf Environment: The Acoustic Clutter Reconnaissance Experiment 2001," J. Acoust. Soc. Am. 117: 1977-1998.
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6. Z. Gong, M. Andrews, S. Jagannathan, R. Patel, J. M. Jech, N. C. Makris, and P. Ratilal, (2010) "Low- frequency target strength and abundance of shoaling Atlantic herring Clupea harengus in the Gulf of Maine during the Ocean Acoustic Waveguide Remote Sensing (OAWRS) 2006 Experiment" J. Acoust. Soc. Am. 127: 104-123.
7. E. T. Küsel and P. Ratilal, (2009) "Effects of incident field refraction on scattered field from vertically extended cylindrical targets in range-dependent ocean waveguides," J. Acoust. Soc. Am. 125: 1930-1936.
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9. M. Andrews, T. Chen, and P. Ratilal, (2009) "Empirical dependence of acoustic transmission scintillation statistics on bandwidth, frequency, and range in New Jersey continental shelf," J. Acoust. Soc. Am. 125(1): 111-124.
10. D. Tran, M. Andrews, and P. Ratilal, (2012) "Probability distribution for energy of saturate broadband ocean acoustic transmission: Results from Gulf of Maine 2006 experiment," J. Acoust. Soc. Am. 132(6): 3659-3672
11. S. Jagannathan, A. D. Jain, and N. C. Makris, "Fluid dynamic equations govern animal group behavior when a simple behavioral rule governs an individual," to be submitted to Phys. Rev. Lett.
12. Z. Gong, A. D. Jain, D. Tran, D. H. Yi, F. Wu, A. Zorn, P. Ratilal, and N. C. Makris, "Ecosystem scale acoustic sensing reveals humpback whale behavior synchronous with herring spawning processes and sonar had no effect on humpback song," submitted to PLoS ONE.

13. Z. Gong, (2012) “Remote Sensing of Marine Life and Submerged Target Motions with Ocean Waveguide Acoustics,” Ph.D. dissertation, Northeastern University, The Department of Electrical and Computer Engineering.

14. Z. Gong, D. Tran, and P. Ratilal, “Passive source localization approaches with a single towed horizontal receiver array in an ocean waveguide,” submitted to J. Acoust. Soc. Am..

15. S. Lee and N. C. Makris, (2006) “The array invariant,” J. Acoust. Soc. Am. 119, 336-351.

16. W. Zhang, H. T. Nia, P. Ratilal, and N. C. Makris, “Nonlinear Scattering of Sound in the Presence of Inhomogeneities,” to be submitted to Phys. Rev. E.